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Accuracy Assessment of Perimeter and Area Calculations Using Consumer-Grade GPS Units in Southern Forests

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Accuracy Assessment of Perimeter and Area Calculations Using Consumer-Grade Global Positioning System (GPS) Units in Southern Forests

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ABSTRACT

Field foresters have long required a method of accurate measurement of perimeter and area during forest management activities. Perimeter and area assessments that can be derived from individual waypoints collected via global positioning system (GPS) units can be an expensive endeavor. A question of concern for practicing foresters is as the cost of GPS units increase does the accuracy of waypoints and any derived perimeter and area assessments also increase? This research evaluated whether the dynamic collection of waypoints using consumer-grade GPS units ranging from $50 to $700 provide a sufficient level of accuracy for the calculation of perimeter and area under three types of canopy cover: a newly established 3-year-old pine plantation, a 13-year-old pine plantation nearing first thinning, and a 40-year-old mixed pine/hardwood stand. Perimeter and area accuracy was not related to cost indicating that inexpensive GPS units provide an accurate waypoint location when used to derive perimeter and area measurements. When compared to a professional survey of each cover type, the average perimeter root mean square error (RMSE) ranged from 18.72 ft (0.41% of total perimeter) in the 40-year-old mixed pine/hardwood stand to 108.50 ft (2.43% of total perimeter) in the 13-year-old pine plantation. The average area RMSE observed ranged from 0.07 acres (0.22% of total acreage) in the 3-year-old plantation to 1.32 acres (4.67% of total acreage) in the 13-year-old pine plantation. For many forestry applications needing a perimeter and acreage assessment, these levels of accuracy should be more than sufficient.

Keywords: accuracy, GPS, forest, RMSE, measurement

The first commercially available global positioning system (GPS) unit, the Texas Instruments TI-411, was introduced in 1982. This GPS unit was barely portable, weighing 53 pounds and measuring 14.7 × 7.5 × 8.5 in. The hardware retailed for $119,000, and postprocessing hardware and software cost another $19,000 (Smithsonian 2009). The GPS unit was capable of tracking four satellites at a time and was theoretically accurate to around 14 m; when differentially corrected, it could be accurate to 2–5 m. In 1989, Magellan introduced the world's first consumer GPS unit, the NAV 1000. A rather large GPS unit by today's standards, it measured 7.5 × 2.5 × 2 in. and weighed almost 2 pounds. It was a single channel receiver, capable of tracking only four satellites, was accurate to 30–45 m, and cost nearly $2,500 (Ashtech 2010). By comparison, the Garmin Oregon 300 released in 2008 measures 4.5 × 2.3 × 1.4 in., weighs 6.8 ounces, is a 20-channel receiver capable of receiving all visible satellite signals simultaneously, and has a stated accuracy of less than 5 m. The manufacturer's suggested retail price for this GPS unit is $500, but it may be found in the $250–$350 price range (Garmin 2009).

Great strides have been made, and continue to be made, in the area of affordable consumer-grade GPS units. Advances in storage capacity, processing power, and display resolution have exponentially increased the power and capabilities of these devices. While submeter-mapping-grade and centimeter-level survey-grade GPS devices are available for use in forest applications, they can be cost prohibitive, especially for many smaller companies. With the ability of many consumer-grade GPS units to incorporate real-time Satellite-Based Augmentation System (SBAS) signals such as Wide Area Augmentation systems (WAAS), the opportunities for the use of such devices in forestry present themselves. Furthermore, recent advances in receiver technology, such as the highly sensitive SiRF-Star III GPS microcontroller chip that is incorporated into many of today's consumer-grade GPS units, claim to have great advantages over previous GPS chipsets under a closed canopy forest (Sirf Technology 2009).

Wing and Eklund (2007) listed several common limitations of consumer-grade GPS receivers, including the inability to set minimum standards of satellite geometry for data collection, a data storage limit of 500 coordinate pairs, and the inability to differentially correct data. Two of these limitations still exist in most consumer-grade GPS units, with some exceptions. The Delorme Earthmate Blue Logger and Trimble Juno ST both have the ability to differentially correct data using relevant software. Unfortunately, that software is currently unavailable for the Delorme Earthmate Blue

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This article uses a metric unit; the applicable conversion factor is: meters (m): 1 m = 3.3 ft.

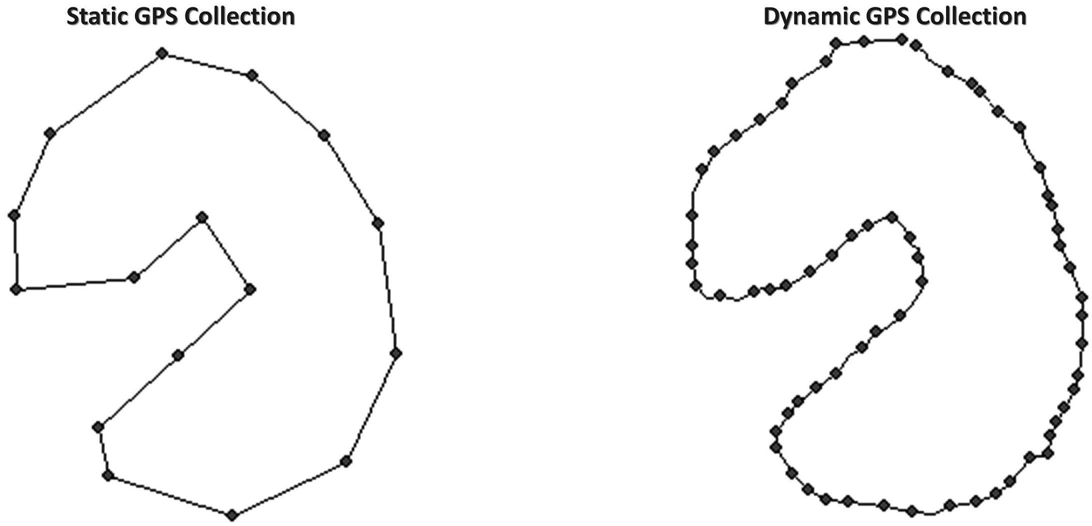

Figure 1. Static versus dynamic GPS data collection.

Logger and expensive enough to put it out of the range of the average forester in the case of the Trimble Juno ST (Trimble 2009).

There were two defining moments that increased the accuracy of consumer-grade GPS units. The first was when selective availability was turned off on May 1, 2000 (PNT 2010). The second was WAAS, which was implemented for testing in 1999 and became generally available on May 10, 2009. The combination of these two events with the advances in computing power and design of the GPS units themselves has increased the accuracy of these GPS units from around 20–100 m in the worst conditions to approximately 2–5 m in most cases and has made them a staple of most practicing foresters (FAA 2010).

Survey and mapping grade GPS receivers can provide the accuracy and precision required by field foresters but are often prohibitively expensive and cumbersome for day-to-day use. Consumer-grade GPS units are very portable and relatively inexpensive, but they lack the accuracy and precision that is available on the higher-grade GPS units. Static or fixed data collection has advantages in the mapping of features in forest settings while the dynamic collection of points is particularly suited to efficient mapping of curvilinear features like a clearcut or streamside management zone (SMZ) (Linehan 2006). As access to consumer-grade GPS units in forest management activities is more common than access to more expensive grades, understanding the accuracy of these GPS units in a dynamic setting becomes more important, allowing a user to use the GPS units to the fullest capacity for perimeter and area calculation.

In addition, perimeter and area calculated from uncorrected waypoint data or simplified waypoint data where extraneous waypoints have been excluded or smoothed to represent the curvilinear nature of any collected polyline need to be considered. The major concern to a practicing forester is what type of GPS unit will provide the level of accuracy required for most field applications and will the accuracy of GPS collected waypoints and any derived length and area measurements increase as the cost of GPS units increase?

Background

GPS in a Forested Environment

The use of a GPS unit in a forest environment presents many challenges. The canopy blocks and degrades satellite signals and tree structure introduces multipath error. Studies that have examined this effect concentrated primarily on horizontal accuracy of GPS units at a stationary point under varying types of forest canopy. Sigrist et al. (1999) found that canopy has a definite effect on horizontal and vertical positioning accuracy and the relation appeared to be exponential; a small increase in canopy density resulted in a substantial increase in error. Yoshimura and Hasegawa (2003, 2006) found that horizontal positioning accuracy and precision errors were highest in areas of dense canopy cover ($\geq 70\%$) and lowest in areas of sparse canopy cover ($\leq 30\%$). Wing et al. (2005) found that consumer-grade GPS receivers were accurate within 5 m under open sky, 7 m under young canopy, and within 10 m under closed canopy in western Oregon. A study by Bolstad et al. (2005) confirmed the ability of GPS receivers to achieve locational accuracy with average errors of 6.5 and 7.1 m within dense forests in Minnesota that was within 10 m reported by Wing et al. (2005).

Piedallu and Gegout (2005) tested three mapping-grade GPS units and one consumer-grade GPS unit and found that denser cover and bigger diameter stems caused a deterioration of accuracy. Zheng et al. (2005) evaluated the static performance of a mapping-grade GPS under three different canopy closure levels in the Pacific Northwest and found that canopy density can significantly affect the positional accuracy of GPS receivers at the $P = 0.01$ level. Rodriguez-Perez (2007) evaluated four consumer-grade GPS receivers and indicated differences under varying forest canopy cover and found significant differences in the models.

Dynamic GPS Collection Method

Dynamic GPS collection is a method of taking GPS measurements at a specified timed interval while the operator moves along the feature to be mapped. This differs from a static or "point to point" method of mapping a feature in which the operator collects a stationary point on the traverse for a specified period of time then moves on to another point along traverse and collects another stationary point without collecting data while en route from one traverse point to another (Figure 1). The static method of mapping is useful and often employed for mapping of simple polygons where high accuracy is required. However, it is time and cost prohibitive for large irregular polygons and curvilinear features such as a stream or road (Tachiki et al. 2005).

A field study conducted by Yawn and Holley (2006) suggests that area calculation with dynamic point collection utilizing mapping-grade GPS units under forest canopy is within a usable range (error being under 3%). While the units were classified as mapping grade for the purposes of their field study, they exhibited similar technical specifications to the units used in this study and fall into the price range specified as consumer grade.

In 2002, the Missouri Precision Agriculture Center compared the accuracy of a consumer-grade GPS unit with WAAS enabled to a mapping-grade GPS receiver for the purposes of crop yield mapping. The consumer-grade unit showed a relative positioning difference of 7.9 ft compared to the mapping-grade unit. The crop yield maps produced from each GPS unit's data showing variability and yield showed no visual differences, and management zones interpolated from the data showed 65–80% similarity between the two GPS units (Shannon et al. 2002).

Real-Time Differential GPS

SBAS is a collection of satellite systems that provide real-time corrections data to GPS receivers. The system in use in North America is WAAS, which consists of 38 ground reference stations in the United States, Canada, and Mexico. The stations monitor GPS satellite data and transfer that data to three master stations that then upload correction messages (error) to multiple geosynchronous satellites. These satellites in turn distribute the correction message to GPS receivers that can apply the real-time corrections in the field to increase waypoint accuracy (Arnold and Zandbergen 2011, FAA 2010).

Federal Aeronautics Administration (FAA) specifications require that WAAS will provide 7.6 m horizontal accuracy, a sizable improvement on the 10–15 m accuracy that is usually specified for most consumer-grade GPS units gathering data autonomously. Quarterly testing by the FAA shows that WAAS accuracy is typically substantially better than the required 7.6 m accuracy, with tests from the first quarter of 2008 indicating that 95% horizontal and vertical accuracy at all evaluated sites were less than 2 m for both WAAS operational service levels (FAA 2008).

Polyline Generalization

Polyline "simplification" is a process of reducing the number of points present on a polyline while still approximating the shape of the original polyline. One of the two algorithms used in ESRI ArcGIS tool Simplify Line is the Point Remove, which is based on the Douglas and Peucker algorithm with enhancements. In the Douglas and Peucker algorithm, the first and last points of a polyline are connected by a trend line and remaining points are tested for closeness to that edge. If any of the points are further from the edge than the specified tolerance, a new polyline is formed that has two edges. The other is the Bend Simplify algorithm that uses shape recognition techniques to detect bends, analyze their characteristics, and eliminate the insignificant bend based on specified parameters. In this method a linear feature is seen as a series of bends. Each bend is compared to a half circle, the diameter of which equals the specified generalization tolerance. This comparison determines whether the bend is kept or replaced by a line connecting the bends endpoints (ESRI 2008, Wang 1996).

Polyline "smoothing" in ArcGIS uses the Smooth Line tool to smooth a line, improving its aesthetic quality using either the polynomial approximation with exponential kernel algorithm (PAEK) or the BEZIER algorithm. PAEK calculates smoothed lines using a continuous local averaging technique with a convolution kernel. The BEZIER algorithm option of this tool combines two steps, the first of which is simplification to reduce the number of vertices in the original data, producing a subset. The tool then fits Bezier curves through each line segment of the subset along an input line. The Bessel tangent is used to make those curves connect smoothly at vertices. A study by Tachiki et al. (2005) evaluated the effects of polyline generalization on consumer-grade GPS under two levels of forest canopy. It found that the effects of polyline generalization were not statistically significant with respect to the calculation of area but were significant with respect to the calculation of perimeter.

Methods

This study was undertaken during early May 2010 to evaluate the ability of consumer-grade GPS units to dynamically measure a polygon or a polyline which forms later as a polygon, which was used to calculate perimeter and area under three forest cover types. This was accomplished by: (1) delineating the boundaries of the three study sites and then performing a conventional survey to record and calculate true position, perimeter, and area statistics; (2) recording perimeter and area statistics for each study site with four different consumer-grade GPS units; (3) comparing surveyed perimeter and area to perimeter and area derived from respective GPS units; and (4) comparing perimeter and area statistics after polygon generalization techniques were applied to the files derived from the GPS units.

The study area was comprised of three separate, approximately 30-acre study sites of distinct age and composition established in three adjoining stands located in Tyler County, Texas. Each study site was located within a half mile radius of each other to facilitate rapid data collection by simplifying logistics. The sites were gently to moderately sloped and situated at approximately 240–270 ft above mean sea level. Species composition was predominantly loblolly pine (*Pinus taeda*), with an understory of yaupon (*Ilex vomitoria*), sweet gum (*Liquidambar styraciflua*), Florida maple (*Acer barbatum*), Chinese tallow (*Sapium sebiferum*), and flowering dogwood (*Cornus florida*) as the primary species.

The first study site was a 3-year-old pine plantation with 10% canopy cover, nearly open to the sky on the interior, and canopy cover around the boundary. The second site was a 13-year-old pine plantation with an average 75.5% canopy cover. The third site was a thinned mixed pine/hardwood stand approximately 40 years old with an average percent canopy cover of 73.4%. For all sites average canopy closure was determined using a spherical densitometer, collecting measurements spaced equally around the perimeter of each study site.

Four consumer-grade GPS units, identified in Table 1, were chosen for their price, features, and availability, and set up to take advantage of any real-time corrections available to the GPS unit. The Trimble Juno ST has capabilities for both real-time (SBAS) and postprocessed differential correction using the Trimble GPSCorrect Extension to ArcGIS. The Delorme Earthmate Blue Logger is capable of applying real-time (SBAS) and postprocessed corrections using the GPS PostPro2 software, which unfortunately has been unavailable since mid-2008. The Garmin ETrex Legend Cx and the Garmin Oregon 300 are capable of applying SBAS corrections.

The study sites were first delineated, and vertices or points of intersection along the perimeter were established and marked with stakes and flagging tape. A lane was established and cleared between each vertex, with a rectilinear line delineated by a string stretched

Table 1. GPS receiver specifications per unit.

	Delorme Earthmate	Garmin eTrex	Garmin Oregon 300	Trimble
	Blue Logger	Legend Cx		Juno St
Cost (USD)	$50	$164	$375	$699
Release date	2004	2006	2008	2007
SBAS supported	Yes	Yes	Yes	Yes
SBAS protocols	WAAS/EGNOS/MSAT	WAAS	WAAS	WAAS/EGNOS/MSAT
Stated accuracy (with SBAS)	Not stated (2–5 m)	> 3 m	> 3–5 m	2–5 m
Stated accuracy (GPS only)	Not stated (> 10 m)	> 15 m	> 10 m	> 10 m
Postprocessing supported	Yes	No	No	Yes
Postprocessing accuracy	> 1 m stated	NA	NA	1–3 m stated
Number of channels	12	12	12	12
Update rate	2 seconds	1 second	1 second	1 second
Power source	Removable/rechargeable	2 AA Batteries	2 AA Batteries	Rechargeable
Battery life	8	12	16	8 h
User interface	USB	Thumb stick	Touchscreen	Touchscreen
Display	None	Mono 288 × 60	Color 240 × 400	Color 240 × 320
Storage	Not Stated	24 mb	850 mb	128 mb
Expandable storage	None	MicroSD	MicroSD	MicroSD
External antenna	Yes	No	No	Yes
Waypoints storable	50,000	500	1,000	Limited to memory
Ruggedized	No	Yes	Yes	No
Waterproof	No	IPX 7	IPX7	No

Table 2. Surveyed perimeter, area, and relative precision per study site.

Forest cover type	Surveyed perimeter (ft)	Surveyed area (acres)	Relative precision
3-year-old pine plantation	6,289.54	32.29	1:8,295
13-year-old pine plantation	4,462.21	28.43	1:5,700
40-year-old mixed	4,591.93	29.87	1:6,400

between vertices and painted with fluorescent orange marker paint for ease of identification while in the field. Brush and small trees less than 2 in. were cleared to create an approximately 4-ft wide trail. An attempt was made for each point of intersection of the trail to be at least 200 ft long, but this was not practical for some places.

Each site was surveyed by Donald Ogden, Texas Registered Professional Land Surveyor, using a Topcon GTS-325 Total Station. The angle and distance between each of the points of intersection were measured twice to minimize error in the conventional survey. After the survey of each site was completed, the total perimeter and acreage of each site was computed by Donald Ogden. Total perimeter length and enclosed area were calculated by connecting each of the points to provide a true baseline assessment of perimeter and area including relative precision, which calculates the ratio between the linear misclosure of a closed-polygon traverse and the total traverse length when plotting the polygon (Table 2).

A 6 × 18 in. platform for the back of an all-terrain vehicle (ATV) was constructed for the mounting of all four GPS units for simultaneous data collection. This platform placed the GPS units at 5 ft 4 in. above the ground, just higher than the ATV driver, to minimize any direct blockage of signal from either the ATV or its pilot. Each GPS unit had a designated place on the platform and was secured to the platform using zip ties before each data collection day.

Prior to data collection, all GPS units were powered on and allowed to run for 30 minutes in a nearby area with minimal obstruction of the sky to ensure that as many satellites as possible were identified by each GPS unit and incorporated into the solution. WAAS was enabled on each GPS unit. Data collection was enabled at the starting point for each GPS unit, and the perimeter of each site was driven at a slow steady pace of approximately 3–4 mph following the line delineated in orange between marked vertices to allow for the dynamic data collection. The ATV was driven at 3–4 mph to mimic the average walking speed of a field forester. An ATV was chosen for data collection due to the length of all three perimeters ranging from 4,462 to 6,290 ft. Waypoint collection due to the use of an ATV in lieu of walking did not bias data collection since only stems less than 2 in. in diameter were removed resulting in no effect on canopy multipath error. Each study site was recorded twice within each test day—one in the early morning (8:00–11:00 am) and the other in the afternoon (3:00–6:00 pm). The study times were not chosen with the intent to conduct the testing during times of highest satellite availability but rather to conduct the testing during times of the day when a field forester would most likely be collecting data in the field. A total number of six rounds of GPS boundary surveys were conducted for each GPS unit in each of the three sites. One exception is for the eTrex unit, which had a total of eight runs on the 3-year site. However, some units failed to capture the boundary feature during field operation and resulted in a sample size less than six.

On completion of the data collection phase, data from each GPS unit were loaded into ArcGIS for analysis. In most cases, this step required an intermediate program to import data from the GPS units and another program to export the GPS file as a polyline shape file. The Garmin GPS units used Garmin Basecamp, and the Delorme Earthmate Blue Logger used Blue Logger Manager to import the files into the computer, while the output from the Trimble Juno ST was directly imported into ArcGIS. The output of the Garmin Basecamp program was converted into a polyline shape file using Expert GPS, a software package produced by TopoGraphix. The output of Blue Logger Manager was a comma delimited text file that first had to be processed in Microsoft Excel and then imported into ArcGIS using the Make XY Event Layer tool.

Once imported into ArcGIS 10.0, these polyline shape files were projected into Universal Transverse Mercator (UTM) NAD83 Zone 15 North and converted into polygons using the "Make one polygon from polylines" tool in XTools 7.1 extension for ArcView. In many cases, this required the removal of extraneous points gathered at the beginning and the end of each collection cycle. In the case

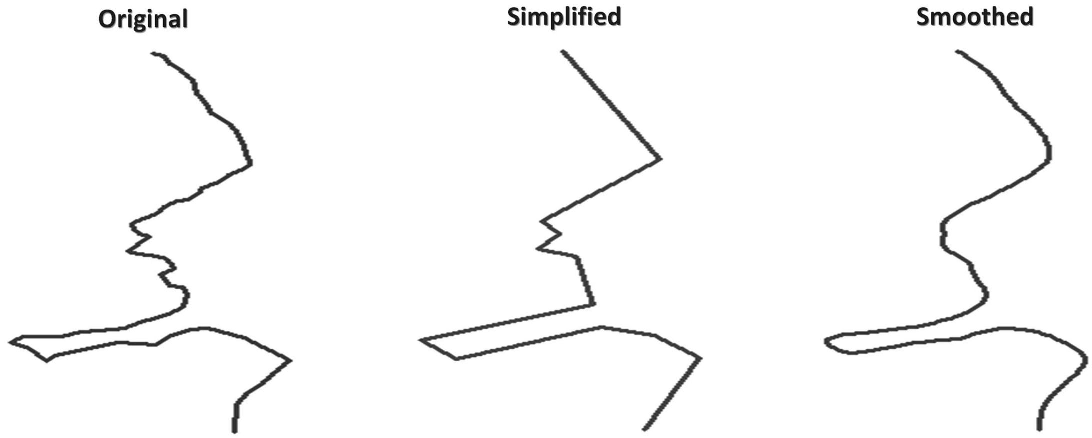

Figure 2. Diagram of original, simplified and smoothed polyline generalization.

Table 3. Mean RMSE (and sample size) of perimeter by polyline generalization, forest cover type, and GPS unit.

	Mean RMSE (ft)	GPS unit type			
Generalization	Forest cover type	Blue Logger	eTrex	Oregon	Juno ST
"None"	3-year-old pine plantation	25.973 (5)	72.626 (8)	55.100 (6)	35.813 (6)
	13-year-old pine plantation	39.832 (6)	64.081 (6)	62.836 (6)	75.682 (5)
	40-year-old mixed	33.931 (5)	18.720 (5)	55.117 (6)	59.707 (6)
"Simplify"	3-year-old pine plantation	30.031 (5)	63.894 (8)	24.307 (6)	74.802 (6)
	13-year-old pine plantation	52.394 (6)	71.199 (6)	62.435 (6)	108.503 (5)
	40-year-old mixed	60.580 (5)	77.631 (5)	36.525 (6)	82.449 (6)
"Smooth"	3-year-old pine plantation	20.184 (5)	25.559 (8)	42.832 (6)	56.167 (6)
	13-year-old pine plantation	51.595 (6)	22.431 (6)	53.274 (6)	81.392 (5)
	40-year-old mixed	27.182 (5)	36.373 (5)	42.450 (6)	51.758 (6)

of intersections of points that prohibited the creation of a polygon, points were removed with as minimal disturbance as possible to the integrity of the line; often this was accomplished with the removal of a single point. Next, total perimeter in feet and acreage were calculated for each polygon using Xtools 7.1 "Calculate" tool. Postprocessing was then performed using two polyline generalization tools, Simplify and Smooth (Figure 2). With the Simplify tool, the point remove generalization algorithm was used with a maximum allowable offset of 10 ft. The Smooth tool used the PAEK algorithm with a smoothing tolerance of 10 ft. Following each polyline generalization technique the perimeter and total acreage was again calculated and recorded. Given that simplify and smoothing generalization were applied to the data collected via an ATV in lieu of walking, removing extraneous points or fitting the data to a curved line for simplify smoothing, respectively, to correct for multipath error would not affect observation error.

To assess the level of GPS error, RMSE was calculated between the GPS measured and the surveyed baseline, for both perimeter and area (Equation 1).

$$\mathrm{RMSE} = \sqrt{\frac{\Sigma(x_{\mathrm{survey}} - x_{\mathrm{GPS\ Unit}})^2}{n}}$$

This was calculated for each GPS unit within each study site—one with no polyline generalization, one after Simplify polyline generalization, and one after Smooth polyline generalization.

To test for statistical difference on the errors, a three-way Model I Analysis of Variance (analysis of variance [ANOVA]) was conducted, for both perimeter and area. The error comparing each GPS observed value to its true (surveyed) value in absolute form was used as observed values for the analysis. The statistical test was based on a 0.05 level of significance. The three main effects tested were GPS unit ($n = 4$), forest cover type ($n = 3$), and postprocessing ($n = 3$).

Results and Discussion

The average percent canopy cover was very close between the 13-year-old loblolly pine plantation and the 40-year-old mixed pine/hardwood study site with 75.5 and 73.4% canopy cover, respectively. The 13-year-old loblolly pine plantation and the 40-year-old mixed pine/hardwood study sites differed substantially in approximate stems per acre with respective numbers of 375 and 90, as well as average height at 36.6 and 74.5 ft. The 3-year-old loblolly pine plantation had a canopy cover of 10.0%. The variable stand conditions between study sites may have contributed to the RMSE errors observed, both on perimeter and area calculations.

Perimeter

A summary of mean perimeter RMSE by GPS unit type, polyline generalization type, and forest cover type can be found in Table 3. For the 3-year-old pine plantation, the Delorme Earthmate Blue Logger with smooth generalization had the lowest average RMSE at 20.18 ft (0.32%). For the 13-year-old pine plantation, the Garmin eTrex Legend Cx with smooth generalization had the lowest average RMSE at 22.43 ft (0.50%). In the 40-year-old mixed pine/hardwood stand, the Garmin eTrex Legend Cx without generalization had the lowest average RMSE at 18.72 ft (0.41%) (Table 3). According to RMSE, on average the Smooth polyline generalization technique slightly increased perimeter accuracy in several of the GPS

Table 4. Three-way Model I ANOVA for perimeter AE.

Source	Sum of squares	Degrees of freedom	Mean square	F-value	*P*-value
Forest cover	6,906.6	2	3,453.3	3.77	0.0251
GPS unit	28,583.0	3	9,527.7	10.39	<0.0001
Postprocessing	10,421.1	2	5,210.6	5.68	0.0041
Forest cover × GPS unit	3,282.7	6	547.1	0.60	0.7326
Forest cover × postprocessing	1,676.0	4	419.0	0.46	0.7672
GPS unit × postprocessing	20,072.7	6	3,345.5	3.65	0.0020
Cover × GPS × post	12,793.8	12	1,066.1	1.16	0.3139
Error	151,266.1	165	916.8		
Total	237,696.4	200			

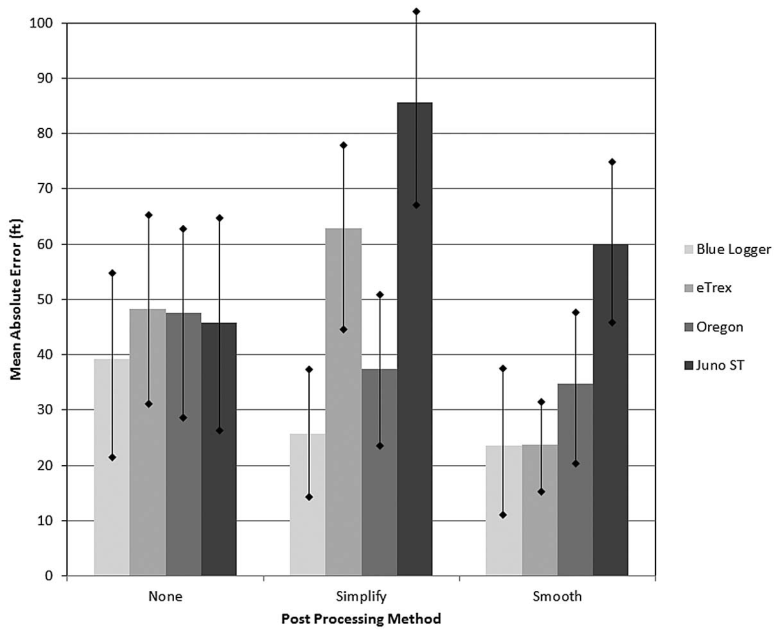

Figure 3. Interaction of post processing method versus GPS unit mean AEs for perimeter.

units. The average perimeter RMSE across all GPS units was nearly 7.5 ft lower than with no polyline generalization and approximately 20 ft lower than the Simplify polyline generalization technique. The range of mean RMSE for the perimeter was not as dramatic with the lowest (40-year-old pine/hardwood by Garmin eTrex Legend Cx without generalization) having 18.72 ft (0.41%) error and the highest (13-year-old pine plantation by Trimble Juno ST with simplification) at 108.50 ft (2.43%).

In the ANOVA, the two-way interaction between GPS unit and postprocessing for the absolute error (AE) of perimeter is significant ($P = 0.0020$), while all other interaction terms are not significant ($P > 0.3$) (Table 4). Because this interaction is highly significant, we cannot directly interpret the results for the three main effects without first considering this interaction (Figure 3). We analyzed the least square means for the levels within this interaction and found three significant results: two within the Simplify postprocessing method and one within the Smooth postprocessing method. For the Simplify method, the AE for the eTrex unit was significantly greater than the Blue Logger unit ($P = 0.0237$) while AE for the Juno unit was significantly greater than the Oregon unit ($P = 0.0003$). For the Smooth method, the AE for the Juno unit was significantly greater than the eTrex unit ($P = 0.0345$). We conclude that all four GPS units perform similarly when no postprocessing is done. We also conclude that for the Simplify postprocessing method, the Blue Logger and Oregon units outperform the eTrex followed by the Juno GPS units; for the Smooth postprocessing method, the Blue Logger, Oregon, and eTrex GPS units perform similarly but outperform the Juno GPS unit.

Forest cover did not significantly interact ($P > 0.7$) with GPS unit or postprocessing. This result allows for interpretation of this simple effect. Error in perimeter significantly differed ($P = 0.0251$) between the three forest cover types. We analyzed the least squares means for forest cover and found that error in perimeter was not significantly different ($P = 0.8535$) between the 3-year-old and 13-year-old forest cover types, but the error in perimeter was significantly higher ($P = 0.0262$) for the 40-year-old cover type.

Area

With regard to area error, essentially the same outcome was observed as with perimeter but more clearly defined (Table 5). For the 3-year-old pine plantation, the Trimble Juno ST without any generalization had the lowest mean RMSE of 0.07 acres (0.22%). For the 13-year-old pine plantation, the Garmin eTrex Legend without any polyline generalization had the lowest mean RMSE of 0.29 acres (1.03%). In the 40-year-old mixed pine/hardwood plantation, the Delorme Earthmate Blue Logger without any polyline generalization had the lowest mean RMSE of 0.43 acres (1.43%). The means of Smooth area RMSE were almost exactly the same as those with no generalization, while the Simplify increased the RMSE slightly by four-hundredths of a point.

The two-way interaction between forest cover type and postprocessing for the absolute error (AE) of area is barely significant ($P =$

Table 5. Mean RMSE (and sample size) of area by polyline generalization, forest cover type, and GPS unit.

	Mean RMSE (acre)	GPS unit type (sample size)			
Generalization	Forest cover type	Blue Logger	eTrex	Oregon	Juno ST
"None"	3-year-old pine plantation	0.114 (5)	0.157 (8)	0.399 (6)	0.070 (6)
	13-year-old pine plantation	0.987 (6)	0.294 (6)	1.317 (6)	0.764 (5)
	40-year-old mixed	0.426 (5)	0.509 (5)	1.024 (6)	0.482 (6)
"Simplify"	3-year-old pine plantation	0.166 (5)	0.230 (8)	0.399 (6)	0.107 (6)
	13-year-old pine plantation	0.986 (6)	0.543 (6)	1.317 (6)	0.778 (5)
	40-year-old mixed	0.426 (5)	0.539 (5)	1.024 (6)	0.479 (6)
"Smooth"	3-year-old pine plantation	0.115 (5)	0.157 (8)	0.397 (6)	0.083 (6)
	13-year-old pine plantation	0.988 (6)	0.309 (6)	1.327 (6)	0.767 (5)
	40-year-old mixed	0.426 (5)	0.509 (5)	1.027 (6)	0.461 (6)

Table 6. Three-way Model I ANOVA for area AE.

Source	Sum of squares	Degrees of freedom	Mean square	F-value	*P*-value
Forest cover	8.9489	2	4.4744	21.37	< 0.0001
GPS unit	4.0413	3	1.3471	6.43	0.0004
Postprocessing	0.0362	2	0.0181	0.09	0.9173
Forest cover × GPS unit	2.7626	6	0.4604	2.20	0.0456
Forest cover × postprocessing	0.0036	4	0.0009	0.01	0.9999
GPS unit × postprocessing	0.0288	6	0.0048	0.02	0.9999
Cover × GPS × post	0.0179	12	0.0015	0.01	0.9999
Error	34.5486	165	0.2094		
Total	30.3550	200			

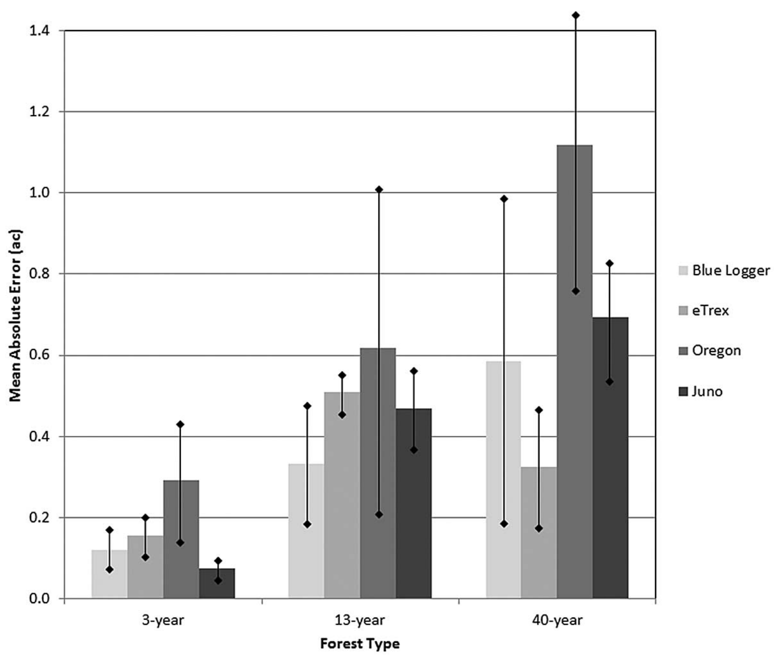

Figure 4. Interaction of cover type versus GPS unit mean AEs for area.

0.0456), while all other interaction terms are not significant ($P >$ 0.9) (Table 6). We analyzed the least square means for the levels within this interaction and found that within each level of forest type, only the eTrex AE was significantly less than the Oregon AE ($P = 0.0001$) for the 40-year-old forest cover type (Figure 4). Because the interaction of the eTrex GPS unit and the 40-year-old forest cover type was the only significant crossover effect, interpretation of some GPS unit and forest cover simple effects is roughly possible. AE for the 3-year-old forest cover type (AE = 0.1600 acre) is significantly lower ($P = 0.0002$) than the 13-year-old forest cover type (AE = 0.4824 acre) and 40-year-old forest cover type (AE = 0.6800 acre, $P < 0.0001$). The 13-year-old cover is significantly lower ($P = 0.0427$) than the 40-year-old cover, except for the eTrex unit. Thus, the lowest AE is associated with the youngest forest, followed distantly by the middle then oldest aged forests in most cases. AE for the Oregon unit (AE = 0.6758 acre) is significantly higher than the Juno unit (AE = 0.4119 acre, $P = 0.0190$), the Blue Logger unit (AE = 0.3458 acre, $P = 0.0043$), and the eTrex unit (AE = 0.3300 acre, $P = 0.0007$). AEs for all other GPS units are not significantly different. There are no significant differences in AE of the postprocessing methods ($P > 0.9$).

Summary and Conclusions

The Delorme Earthmate Blue Logger GPS unit had a respectable average area RMSE, the second lowest average perimeter RMSE, and a long battery life in addition to being the most inexpensive GPS unit. But in practice, it was the hardest to use because it lacks even a rudimentary graphical user interface. In addition, it also had the highest failure rate, five out of the 18 runs. The Garmin eTrex Legend Cx performed very well on average with a low average area RMSE, and the lowest average perimeter RMSE. The Garmin eTrex Legend Cx was also reasonably easy to use and was the second most inexpensive GPS unit in the study. The Trimble Juno ST had the lowest average area RMSE but was almost double the price of the second most inexpensive GPS unit (Garmin Oregon 300). The Garmin Oregon 300 had the most intuitive user interface and was the easiest GPS unit to use, but it had the highest area RMSE under all forest cover types.

In terms of accuracy based on the statistical test on AEs, forest cover type has an impact on area estimation but not perimeter estimation. An older plantation with denser canopy introduces more errors such as multipath error that is in agreement with the RMSE calculation. We also discovered that postprocessing method has an impact on perimeter estimation but not area estimation. Differences in performance exists between GPS units for both area and perimeter estimation. In most cases, the least expensive GPS unit, Blue Logger, outperforms the most expensive GPS units but also has the highest failure rate.

The 3-year-old pine plantation achieving the lowest mean AE on area measurement was attributed by its low canopy cover and low tree height. Oderwald and Boucher (2003) calculated that using a dot grid to estimate area from an aerial photo would have a 3.5% area error while estimating area based on cruise line lengths introduced up to an 8% error. The highest mean percent area error in this study was just under 3% and well within the results obtained by Oderwald and Boucher (2003). In addition, Linehan (2006) indicated that the use of consumer-grade GPS receivers could be used with proper training as accuracy assessment as an alternative to more expensive units. If forest area measurement is the sole goal without concerns for perimeter length, using raw GPS data for area calculation without any generalization process will be satisfactory as no generalization method was found resulting in higher accuracy.

The use of a GPS unit in a forest environment presents many challenges for the user as the forest canopy blocks and degrades satellite signals and tree structure introduces multipath error. However, the dynamic collection of points for the determination of area is much more accurate than traditional methods in open conditions and comparable to traditional methods even under heavy canopy. For many forestry applications, these levels of accuracy should be more than sufficient.

If a practicing forester is solely interested in collected waypoints accuracy and is not concerned about geodatabase development associated with more expensive GPS units then consumer-grade units will suffice in deriving perimeter and area assessments. However, a field forester must make an informed decision of the accuracy needed for each application. For simple linear and area estimation, such as mapping out a clearcut and estimating total acres to order seedlings, an error of 3–5% should suffice. If contracting fire lanes and paying by the quarter mile, a perimeter error of 100 ft in a mile may be well within reason. On the other hand, when surface damages are tabulated by the foot for oil and gas, static collection with a mapping grade GPS or an actual survey may better serve the needs of a field forester.

Literature Cited

Arnold, L., and P. Zandbergen. 2011. Positional accuracy of the Wide Area Augmentation System in consumer-grade GPS units. *Comput. Geosci.* 37(7):883–892.

Ashtech. 2010. About us—Timeline. Available online at www.Ashtech.com/-2667.kjsp; last accessed Jan. 12, 2012.

Bolstad, P., A. Jenks, J. Berkin, K. Horne, and W.H. Reading. 2005. A comparison of autonomous, WAAS, real-time, and post-processed global positioning systems (GPS) accuracies in northern forests. *North. J. Appl. For.* 22(1):5–11.

ESRI. 2008. How simplify line (data management) works. Available online at http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=How%20simplify%20Line%20(Data%20Management)%20works; last accessed Jan. 12, 2012.

FAA. 2008. Wide-area augmentation system performance analysis report. Federal Aviation Administration, William J. Hughes Technical Center, NSTB/WAAS T&E Team Report No. 24, Atlantic City International Airport, New Jersey.

FAA. 2010. WAAS: Quick facts, 2010. Available online at www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/; last accessed Jan. 12, 2012.

Garmin. 2009. *Garmin Oregon Series Owner's Manual.* Garmin International, Inc., Olathe, KS. 48 p.

Linehan, P.E. 2006. Learning geospatial analysis skills with consumer-grade GPS receivers and low cost spatial analysis software. *J. Nat. Res. Life Sci. Edu.* 35:95–100.

Oderwald, R.G., and B.A. Boucher. 2003. GPS after selective availability: How accurate is accurate enough? *J. For.* 101(4):24–27.

Piedallu, C., and J. Gegout. 2005. Effect of forest environment and survey protocol on GPS accuracy. *Photo. Eng. Remote Sens.* 71(9):1071–1078.

PNT. 2010. *Frequently asked questions about selective availability.* Available online at www.gps.gov/systems/gps/modernization sa/faq/; last accessed Jan. 12, 2012.

Rodriguez-Perez, J.R., M.F. Alvarex, and E. Sanz.-Ablanedo. 2007. Assessment of low-cost GPS receiver accuracy and precision in forest environments. *J. Sur. Eng.* 133:159–167.

Shannon, K., C. Ellis, and G. Hoette. 2002. Performance of "low-cost" GPS receivers for yield mapping. ASAE Meeting, Paper No. 02-1151, American Society of Agricultural Engineers, St. Joseph, MI.

Sigrist, P., M. Coppin, and M. Hermy. 1999. Impact of forest canopy on quality and accuracy of GPS measurements. *Intern. J. Rem. Sen.* 20(18):3595–3610.

SIRF Technology. 2009. *SirfStar III product insert rev 1.1.* Available online at www.semiconductorstore.com/pdf/newsite/SiRF/GSD3tw_PB.pdf; last accessed Jan. 12, 2012.

Smithsonian. 2009. *Texas instruments 4100 Navstar navigator, survey and geodesy—Physical sciences collection.* Available online at http://americanhistory.si.edu/collections/surveying/object.cfm?Recordnumber=998407; last accessed Feb. 12, 2012.

Tachiki, Y., T. Yoshimura, H. Hasegawa, T. Mita, T. Sakai, and F. Nakamura. 2005. Effects of polyline simplification under forest canopy on area and perimeter estimations. *J. For. Res.* 10:419–427.

Trimble. 2009. *Trimble GPSCorrect—Getting started guide revision 3.10.* Available online at http://trl.trimble.com/docushare/dsweb/Get/Document-478233/GPScorrectGettingStartedGuide.pdf; last accessed Jan. 12, 2012.

Wang, Z. 1996. Manual versus automated line generalization. P. 94–106 in *GIS/LIS '96 Proceedings*. American Soc. for Photo. and Rem. Sens., Curran Associates, Inc., Red Hook, New York.

Wing, M., A. Eklund, and L. Kellogg. 2005. Consumer-grade global positioning system (GPS) accuracy and reliability. *J. For.* 103(4):169–173.

Wing, M., and A. Eklund. 2007. Performance comparison of a low cost mapping grade global positioning systems receiver (GPS) and consumer grade GPS receiver under dense forest canopy. *J. For.* 105(1):9–14.

Yawn, D., and B. Holley. 2006. Accuracy of various GPS antennas under forested conditions. P. 2–9 in *Proc. of conf. on 5th southern forestry and natural resources GIS conference*. Warnell School of Forestry and Natural Resources, Athens, GA.

Yoshimura, T., and H. Hasegawa. 2003. Comparing the precision and accuracy of GPS positioning in forested areas. *J. For.* Res. 8:143–152.

Yoshimura, T., and H. Hasegawa. 2006. High-end GPS vs. low-end GPS: Comparing GPS positioning accuracy in the forest environment. P. 429–436 in *UFRO precision forestry symposium*, Stellenbosch, South Africa.

Zheng, J., Y. Wang, and N. Nihan. 2005. Quantitative evaluation of GPS performance under forest canopies. P. 777–782 in *Proc. of conf. of the IEEE networking, sensing and control*, IEEE Cat. No. 05EX967, Washington, DC.